

Leachate Geochemistry at a Municipal Landfill, Memphis, Tennessee

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Abstract

A leachate plume emanating from the Shelby County Landfill located at Memphis, Tennessee is defined using selected major and trace inorganic constituents. High specific conductance values and elevated concentrations of ammonia, barium, boron, calcium, chloride, dissolved solids, potassium, sodium, and strontium were measured in water samples from wells screened in the alluvial and Memphis aquifers downgradient from or proximal to the landfill. Of these constituents, barium, boron, chloride, and strontium were used in the geochemical model code PHREEQE to estimate the percent leachate component in selected Memphis aquifer samples. Estimates of the leachate component in samples from affected Memphis aquifer wells range from 5 to 37 percent for barium and strontium, the most reliable tracers found during this study.

Introduction

Leachate plumes from municipal solid-waste landfills are potential sources of contamination to ground-water supplies. Evaluation of the spatial extent and magnitude of leachate contamination is important because elevated concentrations of inorganic and organic compounds in leachate can degrade ground-water quality and contribute to higher treatment costs or abandonment of water-supply wells. Although leachate compositions vary, large specific conductance values, and elevated concentrations of ammonia, dissolved solids, total organic carbon, chloride, iron, and most major cations commonly are detected (for example, Baedeker and Back, 1979). Although leachate plumes may not always have high concentrations of priority pollutants, occasionally federal maximum contaminant levels in ground water are exceeded with respect to volatile organic compounds and trace elements (Bolton and Evans, 1991; Borden and Yanoschak, 1990; Reinhard et al., 1984; Dewalle and Chian, 1981).

This paper describes the geochemistry of a leachate plume emanating from the Shelby County landfill at Memphis, Tennessee based on inorganic constituent concentration data from ground-water samples. These data were used to define the path of the plume from its source at the landfill into the deeper Memphis aquifer.

Defining the geochemical characteristics of the leachate plume in this manner may be applicable to other municipal landfills built on clastic sediment. This work indicates that relatively inexpensive analytes (selected major and trace constituents) can be used to detect leachate contamination

in downgradient wells, as required by U.S. Environmental Protection Agency (1991a; 1991b; 1991c) ground-water monitoring regulations.

This study is an extension of an investigation (Parks and Mirecki, 1992) of the Shelby County landfill conducted from 1989 to 1991 by the U.S. Geological Survey in cooperation with the Shelby County Department of Public Works.

Site History and Description

The Shelby County landfill was operated as a waste-disposal facility from 1968 to 1988, during which unregulated disposal occurred from 1968 to 1972. After 1972, disposal was regulated by the Shelby County Department of Public Works (SCDPW) and only domestic and municipal wastes were accepted. The 90-acre landfill is located on the alluvial plain of the Wolf River, south of Walnut Grove Road (Figure 1). At present, its capped surface is 40 to 45 feet above the alluvial plain, which consists of a forested levee to the southwest, and agricultural land to the southeast and north. The Shelby County landfill was closed in 1988.

Expansion of the landfill north of Walnut Grove Road was considered, which prompted a geologic and hydrologic investigation by the SCDPW in 1986 to evaluate whether expansion of the existing facility was appropriate. During that investigation, water-level measurements in auger holes and observation wells indicated that the potentiometric surface of the alluvial aquifer north of the landfill was depressed below the low-flow altitude of the Wolf River (Bradley, 1991). This anomalous water-level condition was the initial indication that downward leakage of water from the near-surface alluvial aquifer into the underlying Memphis aquifer was taking place.

Hydrogeologic Setting

Near-surface lithologic units beneath the Shelby County landfill include alluvium of Quaternary age and the Memphis Sand of Tertiary age. These units constitute the alluvial and

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Memphis aquifers, respectively. In the upper part of the Memphis Sand, a confining unit consisting of interlensed clay, silt, and fine sand separates the alluvial aquifer from the Memphis aquifer. This confining unit was thought to be laterally extensive near the landfill, thus preventing contamination of the Memphis aquifer, which is the principal source of drinking water for the city of Memphis. However, geophysical log data from test holes and wells indicated that these lenses of clay, silt, and fine sand in the upper part of the Memphis Sand are not laterally continuous throughout the Memphis area (Parks, 1990). In particular, lithologic data from some test holes indicated that the confining unit is discontinuous adjacent to the Shelby County landfill (test hole MS-8 and well MS-12, Figure 1; Parks and Mirecki, 1992).

Identification of a discontinuity in the confining unit allowed an evaluation of ground-water flow direction between the alluvial and Memphis aquifers. Water levels measured in wells screened in the alluvial aquifer near the Wolf River approximated stages of the river. However, a depression in the potentiometric surface of the unconfined alluvial aquifer (as much as 14 feet below the low-flow altitude of the Wolf River) had been defined northeast of the landfill (Figure 2; Bradley, 1991). In the alluvial aquifer, water flows northeast from the Wolf River toward the depression. In the Memphis aquifer, water flows generally to the west (Figure 3), but an anomalous high in the potentiometric surface existed where the confining unit is thin or absent. This anomaly indicates that water level in the Memphis aquifer was elevated as a result of downward leakage from the alluvial aquifer.

Definition of ground-water flow direction enabled interpretation of leachate plume geochemical characteristics as the plume moved downgradient from the landfill source. In the alluvial aquifer, background, upgradient, and down-

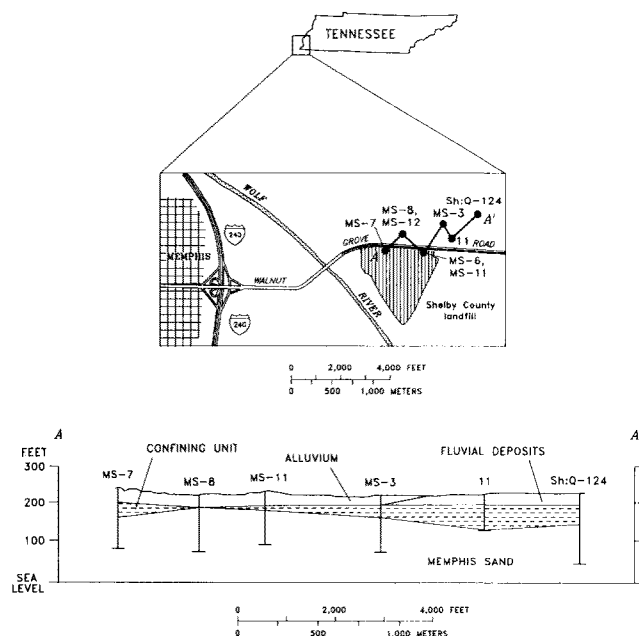


Fig. 1. Location of the Shelby County landfill and geologic section A-A' (modified from Parks and Mirecki, 1992).

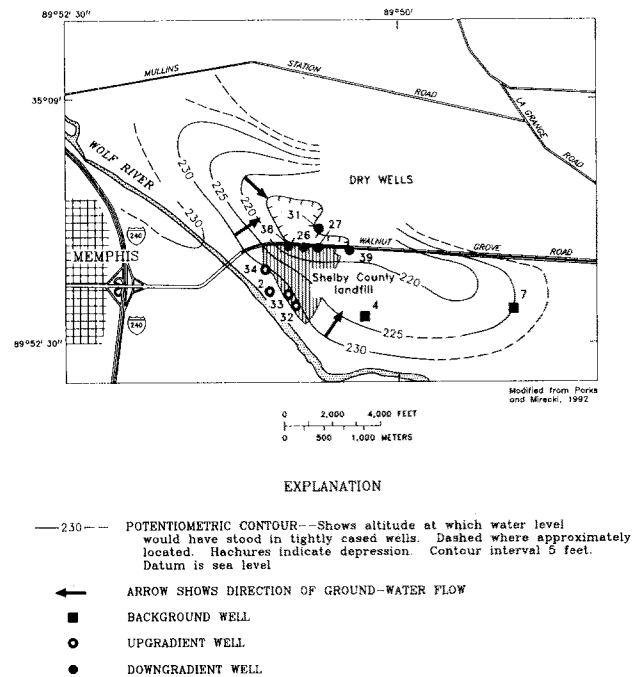


Fig. 2. Altitude of the water table in the alluvial aquifer and location of wells used to trace the leachate plume.

gradient wells were designated relative to the flow path through the landfill (Figure 2). The distinction among background, upgradient, and downgradient wells was clear because the geochemical composition of samples from downgradient wells 26, 27, 31, 38, and 39 differs from that of all other alluvial aquifer wells (Table 1). In the Memphis aquifer, anomalies in the altitude of the potentiometric surface near the landfill resulted from discontinuities in the confining unit, so designation of upgradient and downgradient wells was not clear. Therefore, for the Memphis

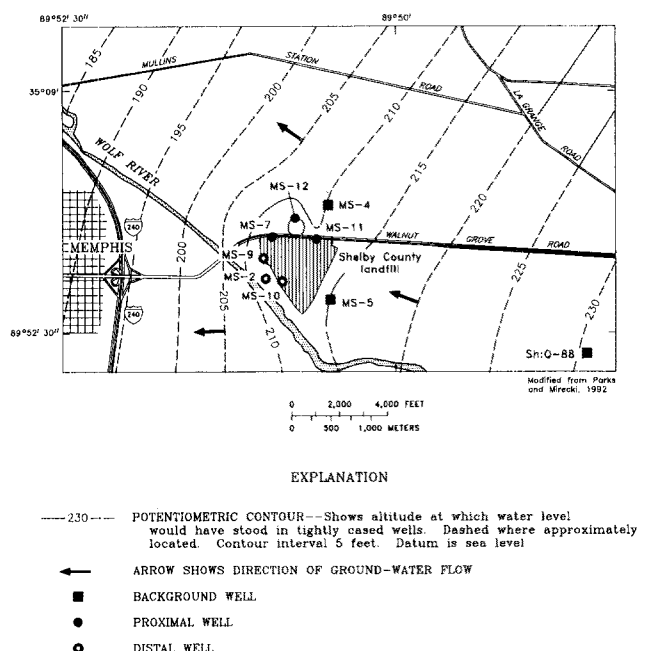


Fig. 3. Altitude of the potentiometric surface of the Memphis aquifer and location of wells used to trace the leachate plume.

Table 1. Mean Values of Dissolved Constituents and Properties of Water for Samples Collected from Wells Screened in the Alluvial Aquifer at the Shelby County Landfill, Memphis, Tennessee

<i>Background wells</i>					
<i>Constituent or property</i>	<i>Well 4</i>		<i>Well 7</i>		<i>Mean +/- standard deviation</i>
Ammonia	0.23	mg/l	0.11	mg/l	0.17 +/- 0.06 mg/l
Bromide	0.03	mg/l	0.09	mg/l	0.06 +/- 0.03 mg/l
Calcium	19	mg/l	34	mg/l	26.5 +/- 7.5 mg/l
Chloride	2.1	mg/l	9.8	mg/l	6.0 +/- 7.5 mg/l
Dissolved solids	132	mg/l	266	mg/l	199 +/- 67 mg/l
Fluoride	<0.10	mg/l	0.25	mg/l	0.18 +/- 0.08 mg/l
Iodide	0.005	mg/l	0.014	mg/l	0.010 +/- 0.005 mg/l
Iron	—		27.5	mg/l	27.5 mg/l
Magnesium	6.4	mg/l	13	mg/l	9.7 +/- 3.3 mg/l
Manganese	—		0.185	mg/l	0.185 mg/l
Nitrate plus nitrate as N	<0.100	mg/l	0.65	mg/l	0.51 +/- 0.34 mg/l
Phosphate as PO ₄	0.21	mg/l	—		0.21 mg/l
Phosphorus as P	0.08	mg/l	0.01	mg/l	0.05 +/- 0.04 mg/l
Potassium	1.9	mg/l	1.9	mg/l	1.9 +/- 0.0 mg/l
Silica	20	mg/l	21.5	mg/l	21 +/- 0.8 mg/l
Sodium	4.6	mg/l	21	mg/l	13 +/- 8.0 mg/l
Sulfate	72	mg/l	140	mg/l	106 +/- 34 mg/l
Total organic carbon	2	mg/l	1.1	mg/l	1.7 +/- 0.6 mg/l
Barium	60	µg/l	83	µg/l	72 +/- 12 µg/l
Boron	<10	µg/l	<10	µg/l	<10 µg/l
Cadmium	3	µg/l	<1	µg/l	2.0 +/- 1.0 µg/l
Chromium	1	µg/l	1	µg/l	1 +/- 0.0 µg/l
Copper	3	µg/l	1.5	µg/l	2.3 +/- 0.8 µg/l
Lead	1	µg/l	<1	µg/l	1 µg/l
Nickel	23	µg/l	3.5	µg/l	13 +/- 10 µg/l
Strontium	89	µg/l	90	µg/l	89 +/- 0 µg/l
Zinc	16	µg/l	7	µg/l	12 +/- 4.5 µg/l
Specific conductance	245	µS/cm	196	µS/cm	220 +/- 24.5 µS/cm
pH	6		5.3		—
<i>Upgradient wells</i>					
<i>Constituent or property</i>	<i>Well 2</i>		<i>Well 32</i>		<i>Mean +/- standard deviation</i>
Ammonia	0.32	mg/l	0.41	mg/l	0.45 +/- 0.09 mg/l
Bromide	0.01	mg/l	0.01	mg/l	0.03 +/- 0.02 mg/l
Calcium	6.3	mg/l	6.4	mg/l	7.4 +/- 1.7 mg/l
Chloride	3.4	mg/l	2.6	mg/l	3.0 +/- 0.4 mg/l
Dissolved solids	42	mg/l	41	mg/l	91.3 +/- 51 mg/l
Fluoride	0.1	mg/l	0.2	mg/l	0.10 +/- 0.06 mg/l
Iodide	0.013	mg/l	0.011	mg/l	0.017 +/- 0.06 mg/l
Iron	5.1	mg/l	3.8	mg/l	6.6 +/- 3.1 mg/l
Magnesium	1.4	mg/l	2.3	mg/l	2.5 +/- 0.9 mg/l
Manganese	0.52	mg/l	0.73	mg/l	0.94 +/- 0.41 mg/l
Nitrate plus nitrite as N	<0.100	mg/l	<0.100	mg/l	<0.100 mg/l
Phosphate as PO ₄	—		0.15	mg/l	0.34 +/- 0.15 mg/l
Phosphorus as P	0.02	mg/l	0.03	mg/l	0.10 +/- 0.08 mg/l
Potassium	2.6	mg/l	1.5	mg/l	1.7 +/- 0.5 mg/l
Silica	9.8	mg/l	12	mg/l	14 +/- 2.9 mg/l
Sodium	3.5	mg/l	3.6	mg/l	3.8 +/- 0.4 mg/l
Sulfate	3	mg/l	2	mg/l	3.6 +/- 1.8 mg/l
Total organic carbon	1.5	mg/l	1.3	mg/l	2.1 +/- 0.7 mg/l
Barium	130	µg/l	59	µg/l	92 +/- 26 µg/l
Boron	20	µg/l	12	µg/l	16 +/- 4.1 µg/l
Cadmium	<1	µg/l	<1	µg/l	1.3 +/- 0.3 µg/l
Chromium	<1	µg/l	<1	µg/l	<1 µg/l
Copper	5	µg/l	<1	µg/l	2.1 +/- 1.6 µg/l
Lead	<1	µg/l	<1	µg/l	<1 µg/l
Nickel	6	µg/l	1	µg/l	4 +/- 3 µg/l
Strontium	46	µg/l	26	µg/l	45 +/- 16 µg/l
Zinc	<3	µg/l	<3	µg/l	3.9 +/- 1.2 µg/l
Specific conductance	90	µS/cm	91	µS/cm	108 +/- 22 µS/cm
pH	6.5		6.3		—

Table 1. Mean Values of Dissolved Constituents and Properties of Water for Samples Collected from Wells Screened in the Alluvial Aquifer at the Shelby County Landfill, Memphis, Tennessee (Continued)

<i>Downgradient wells</i>												
<i>Constituent or property</i>	<i>Well 26</i>		<i>Well 27</i>		<i>Well 31</i>		<i>Well 38</i>		<i>Well 39</i>		<i>Mean +/- standard deviation</i>	
Ammonia	14	mg/l	18	mg/l	0.21	mg/l	1.3	mg/l	3.7	mg/l	7.3	+/- 7.0 mg/l
Bromide	0.25	mg/l	0.43	mg/l	0.06	mg/l	0.04	mg/l	0.17	mg/l	0.19	+/- 0.14 mg/l
Calcium	70.5	mg/l	99.0	mg/l	52.5	mg/l	38.5	mg/l	34	mg/l	59	+/- 24 mg/l
Chloride	56	mg/l	77	mg/l	5.5	mg/l	13	mg/l	3	mg/l	36	+/- 27 mg/l
Dissolved solids	487	mg/l	657	mg/l	444	mg/l	311	mg/l	261	mg/l	432	+/- 140 mg/l
Fluoride	0.15	mg/l	0.15	mg/l	0.15	mg/l	0.20	mg/l	0.20	mg/l	0.14	+/- 0.07 mg/l
Iodide	0.21	mg/l	0.16	mg/l	0.15	mg/l	0.07	mg/l	0.05	mg/l	0.13	+/- 0.06 mg/l
Iron	51	mg/l	57.5	mg/l	0.89	mg/l	105	mg/l	47	mg/l	53.2	+/- 33.1 mg/l
Magnesium	21.5	mg/l	24	mg/l	16	mg/l	13	mg/l	12	mg/l	17	+/- 4.7 mg/l
Manganese	1.15	mg/l	1.8	mg/l	1.6	mg/l	6.5	mg/l	1.3	mg/l	2.5	+/- 2.0 mg/l
Nitrate plus nitrite as N	<0.100	mg/l	<0.100	mg/l	<0.100	mg/l	<0.100	mg/l	<0.100	mg/l	<0.10	mg/l
Phosphate as PO ₄	0.15	mg/l	0.09	mg/l	0.03	mg/l	—		0.06	mg/l	0.08	+/- 0.04 mg/l
Phosphorus as P	0.045	mg/l	<0.010	mg/l	0.025	mg/l	<0.010	mg/l	0.035	mg/l	0.025	+/- 0.014 mg/l
Potassium	25	mg/l	37.5	mg/l	3.2	mg/l	4.7	mg/l	6.7	mg/l	15	+/- 14 mg/l
Silica	14	mg/l	15	mg/l	22	mg/l	17	mg/l	15	mg/l	16	+/- 2.7 mg/l
Sodium	50	mg/l	70	mg/l	92	mg/l	23	mg/l	28	mg/l	52	+/- 26 mg/l
Sulfate	<1	mg/l	3	mg/l	43	mg/l	29	mg/l	1	mg/l	15	+/- 17 mg/l
Total organic carbon	12	mg/l	15	mg/l	1.7	mg/l	2.9	mg/l	4.7	mg/l	7.3	+/- 5.3 mg/l
Barium	845	μg/l	820	μg/l	90	μg/l	275	μg/l	215	μg/l	449	+/- 329 μg/l
Boron	480	μg/l	900	μg/l	25	μg/l	25	μg/l	440	μg/l	374	+/- 327 μg/l
Cadmium	7	μg/l	4	μg/l	<1	μg/l	18	μg/l	4	μg/l	6.8	+/- 5.9 μg/l
Chromium	<1	μg/l	<1	μg/l	<1	μg/l	<1	μg/l	<1	μg/l	<1	μg/l
Copper	<1	μg/l	<1	μg/l	<1	μg/l	<1	μg/l	<1	μg/l	<1	μg/l
Lead	<1	μg/l	<1	μg/l	<1	μg/l	<1	μg/l	<1	μg/l	<1	μg/l
Nickel	7	μg/l	16	μg/l	11	μg/l	12	μg/l	4	μg/l	10	+/- 4 μg/l
Strontium	355	μg/l	770	μg/l	460	μg/l	25	μg/l	120	μg/l	382	+/- 226 μg/l
Zinc	5	μg/l	9	μg/l	22	μg/l	4	μg/l	3	μg/l	8.6	+/- 7.0 μg/l
Specific conductance	989	μS/cm	1205	μS/cm	713	μS/cm	80	μS/cm	552	μS/cm	828	+/- 236 μS/cm
pH	6.3		6.5		6.4		6.3		6.1		—	—

[Units are milligrams per liter (mg/l), micrograms per liter (μg/l), or microsiemens per centimeter (μS/cm) at 25 degrees Celsius; some wells were sampled more than once and values are means for concentrations detected; mean was calculated by dividing the sum of the concentrations by the number of analyses for each well; single values for mean +/- standard deviation shows the concentration detected in one sample; < indicates less than; —, indicates not determined.]

aquifer, background, proximal, and distal wells were designated relative to the discontinuity in the confining unit. Samples from Memphis aquifer wells located proximal to the stratigraphic discontinuity (wells MS-7, MS-11, and MS-12) had statistically significant elevated concentrations of calcium, dissolved solids, potassium, sodium, and strontium compared to samples from distal or background wells (Table 2). The term "statistically significant" is used in this paper to indicate that standard deviations of mean concentration values do not overlap.

Geochemical Characteristics of the Leachate Plume

Because of the landfill's proximity to the area of downward leakage, and the potential for contamination of the Memphis aquifer by the leachate plume, investigations of downward leakage and ground-water quality were conducted by the U.S. Geological Survey from 1986 to 1987 (Bradley, 1991) and 1989 to 1991 (Parks and Mirecki, 1992). Ground-water samples were collected from 12 wells screened in the alluvial aquifer and 9 wells screened in the Memphis aquifer in October 1989 and July 1990. These samples were analyzed for organic and inorganic constituents at the U.S.

Geological Survey National Water Quality Laboratory in Arvada, Colorado.

Samples collected from wells screened in the alluvial aquifer downgradient from the landfill had significantly high specific conductance values and elevated concentrations of ammonia, barium, boron, calcium, chloride, dissolved solids, potassium, sodium, and strontium (Table 1). Chloride is used commonly as a conservative tracer because its concentration is diminished only by dilution (Domenico and Schwartz, 1990; Russell and Higer, 1988; MacFarland et al., 1983). Chloride was tested as a tracer in this investigation despite variable concentrations downgradient in the alluvial aquifer (Table 1).

Barium, boron, and strontium also were used to characterize the leachate plume for several reasons. First, in the alluvial aquifer, downgradient concentrations of barium, boron, and strontium were significantly elevated in comparison to upgradient and background concentrations, in contrast to chloride (Table 1). This comparison indicated that barium, boron, and strontium characterized the leachate plume. Second, these constituents can be incorporated into geochemical models, unlike total dissolved solids concentrations and specific conductance measurements. Third, pre-

Table 2. Mean Values of Dissolved Constituents and Properties of Water for Samples Collected from Wells Screened in the Memphis Aquifer at the Shelby County Landfill, Memphis, Tennessee

<i>Background wells</i>					
<i>Constituent or property</i>	<i>Well MS-4</i>	<i>Well MS-5</i>	<i>Well SH:Q-88</i>	<i>Mean +/- standard deviation</i>	
Ammonia	0.20 mg/l	0.15 mg/l	0.70 mg/l	0.14 +/-	0.05 mg/l
Bromide	0.04 mg/l	0.025 mg/l	0.02 mg/l	0.028 +/-	0.008 mg/l
Calcium	5.1 mg/l	7.6 mg/l	11 mg/l	7.8 +/-	2.2 mg/l
Chloride	3 mg/l	4 mg/l	31 mg/l	12 +/-	13 mg/l
Dissolved solids	116 mg/l	123 mg/l	98 mg/l	112 +/-	11 mg/l
Fluoride	0.2 mg/l	0.15 mg/l	<0.1 mg/l	0.15 +/-	0.05 mg/l
Iodide	0.02 mg/l	0.011 mg/l	0.004 mg/l	0.012 +/-	0.006 mg/l
Iron	0.16 mg/l	0.05 mg/l	0.32 mg/l	0.17 +/-	0.11 mg/l
Magnesium	5.1 mg/l	7.6 mg/l	4.3 mg/l	5.7 +/-	1.4 mg/l
Manganese	0.069 mg/l	0.14 mg/l	0.048 mg/l	0.085 +/-	0.04 mg/l
Nitrate plus nitrite as N	<0.100 mg/l	<0.100 mg/l	<0.100 mg/l	<0.100	mg/l
Phosphate as PO ₄	0.09 mg/l	0.03 mg/l	—	0.06 +/-	0.03 mg/l
Phosphorus as P	<0.010 mg/l	<0.010 mg/l	<0.010 mg/l	<0.010	mg/l
Potassium	1.1 mg/l	0.9 mg/l	0.8 mg/l	0.9 +/-	0.1 mg/l
Silica	12 mg/l	17 mg/l	15 mg/l	15 +/-	1.9 mg/l
Sodium	8.7 mg/l	7.1 mg/l	17 mg/l	11 +/-	1.4 mg/l
Sulfate	3 mg/l	26 mg/l	5.6 mg/l	11 +/-	10 mg/l
Total organic carbon	2.4 mg/l	10.9 mg/l	0.2 mg/l	4.5 +/-	4.6 mg/l
Barium	82 µg/l	58 µg/l	33 µg/l	57 +/-	20 µg/l
Boron	<10 µg/l	15 µg/l	<10 µg/l	12 +/-	2.4 µg/l
Cadmium	<1 µg/l	<1 µg/l	<1 µg/l	<1	µg/l
Chromium	<1 µg/l	<1 µg/l	<1 µg/l	<1	µg/l
Copper	1 µg/l	<1 µg/l	<1 µg/l	<1	µg/l
Lead	1 µg/l	<1 µg/l	<1 µg/l	<1	µg/l
Nickel	1 µg/l	2.5 µg/l	1.5 µg/l	1.7 +/-	0.6 µg/l
Strontium	57 µg/l	65 µg/l	31 µg/l	51 +/-	15 µg/l
Zinc	27 µg/l	38 µg/l	10 µg/l	25 +/-	11 µg/l
Specific conductance	253 µS/cm	206 µS/cm	175 µS/cm	211 +/-	32 µS/cm
pH	6.9	6.2	6.0	—	—
<i>Proximal wells</i>					
<i>Constituent or property</i>	<i>Well MS-7</i>	<i>Well MS-11</i>	<i>Well MS-12</i>	<i>Mean +/- standard deviation</i>	
Ammonia	0.085 mg/l	2.7 mg/l	0.050 mg/l	0.954 +/-	1.2 mg/l
Bromide	0.07 mg/l	0.565 mg/l	0.035 mg/l	0.22 +/-	0.24 mg/l
Calcium	30 mg/l	56 mg/l	46 mg/l	44 +/-	11 mg/l
Chloride	10 mg/l	61 mg/l	8.4 mg/l	27 +/-	24 mg/l
Dissolved solids	157 mg/l	350 mg/l	282 mg/l	263 +/-	80 mg/l
Fluoride	0.2 mg/l	0.1 mg/l	0.2 mg/l	0.17 +/-	0.05 mg/l
Iodide	0.023 mg/l	0.12 mg/l	0.025 mg/l	0.056 +/-	0.045 mg/l
Iron	1.46 mg/l	2.7 mg/l	0.034 mg/l	1.39 +/-	1.09 mg/l
Magnesium	7.1 mg/l	19 mg/l	0.11 mg/l	8 +/-	8 mg/l
Manganese	0.181 mg/l	0.215 mg/l	0.21 mg/l	0.202 +/-	0.015 mg/l
Nitrate plus nitrite as N	<0.100 mg/l	<0.100 mg/l	<0.100 mg/l	<0.100	mg/l
Phosphate as PO ₄	0.09 mg/l	— mg/l	0.12 mg/l	0.11 +/-	0.02 mg/l
Phosphorus as P	0.02 mg/l	0.015 mg/l	0.035 mg/l	0.023 +/-	0.008 mg/l
Potassium	1.2 mg/l	3.7 mg/l	2.3 mg/l	2.4 +/-	1.0 mg/l
Silica	13 mg/l	9.8 mg/l	29 mg/l	17 +/-	8.4 mg/l
Sodium	14 mg/l	46 mg/l	40 mg/l	33 +/-	14 mg/l
Sulfate	22 mg/l	26 mg/l	63 mg/l	37 +/-	18 mg/l
Total organic carbon	1.3 mg/l	6.3 mg/l	1.9 mg/l	3.2 +/-	2.2 mg/l
Barium	81 µg/l	87 µg/l	77 µg/l	82 +/-	4.0 µg/l
Boron	25 µg/l	65 µg/l	25 µg/l	38 +/-	17 µg/l
Cadmium	<1 µg/l	<1 µg/l	<1 µg/l	<1	µg/l
Chromium	<1 µg/l	<1 µg/l	<1 µg/l	<1	µg/l
Copper	1 µg/l	2 µg/l	2 µg/l	2 +/-	1 µg/l
Lead	<1 µg/l	<1 µg/l	<1 µg/l	<1	µg/l
Nickel	3 µg/l	8 µg/l	3 µg/l	5 +/-	2 µg/l
Strontium	83 µg/l	130 µg/l	171 µg/l	128 +/-	36 µg/l
Zinc	22 µg/l	83 µg/l	44 µg/l	50 +/-	25 µg/l
Specific conductance	256 µS/cm	628 µS/cm	432 µS/cm	438 +/-	152 µS/cm
pH	6.2	6.1	6.1	—	—

Table 2. Mean Values of Dissolved Constituents and Properties of Water for Samples Collected from Wells Screened in the Memphis Aquifer at the Shelby County Landfill, Memphis, Tennessee (continued)

Constituent or property	Distal wells				Mean +/- standard deviation	
	Well MS-2	Well MS-9	Well MS-10			
Ammonia	0.085 mg/l	0.045 mg/l	0.045 mg/l	0.058 +/-	0.019 mg/l	
Bromide	0.02 mg/l	0.03 mg/l	0.04 mg/l	0.030 +/-	0.010 mg/l	
Calcium	14 mg/l	13 mg/l	15 mg/l	14 +/-	1 mg/l	
Chloride	3.1 mg/l	11.8 mg/l	1.8 mg/l	5.6 +/-	4.4 mg/l	
Dissolved solids	74 mg/l	72 mg/l	101 mg/l	82 +/-	13 mg/l	
Fluoride	0.15 mg/l	0.1 mg/l	0.1 mg/l	0.12 +/-	0.02 mg/l	
Iodide	0.017 mg/l	0.034 mg/l	0.025 mg/l	0.025 +/-	0.007 mg/l	
Iron	0.495 mg/l	1.141 mg/l	0.405 mg/l	0.35 +/-	0.15 mg/l	
Magnesium	3.4 mg/l	4.8 mg/l	5.3 mg/l	4.5 +/-	0.8 mg/l	
Manganese	0.16 mg/l	0.235 mg/l	0.213 mg/l	0.197 +/-	0.038 mg/l	
Nitrate plus nitrite as N	<0.100 mg/l	<0.100 mg/l	<0.100 mg/l	<0.100	mg/l	
Phosphate as PO ₄	0.06 mg/l	— mg/l	0.03 mg/l	0.03 +/-	0.03 mg/l	
Phosphorus as P	0.035 mg/l	0.025 mg/l	0.01 mg/l	0.023 +/-	0.010 mg/l	
Potassium	1 mg/l	1.3 mg/l	0.9 mg/l	1.2 +/-	0.2 mg/l	
Silica	9.7 mg/l	11 mg/l	9.9 mg/l	10 +/-	0.6 mg/l	
Sodium	3.5 mg/l	4.3 mg/l	5.3 mg/l	4.4 +/-	0.9 mg/l	
Sulfate	3.6 mg/l	2.5 mg/l	2.8 mg/l	3.0 +/-	0.5 mg/l	
Total organic carbon	36 mg/l	46 mg/l	18 mg/l	33 +/-	12 mg/l	
Barium	82 µg/l	106 µg/l	41 µg/l	76 +/-	27 µg/l	
Boron	10 µg/l	25 µg/l	25 µg/l	20 +/-	7.1 µg/l	
Cadmium	2.5 µg/l	<1 µg/l	<1 µg/l	<1	µg/l	
Chromium	<1 µg/l	<1 µg/l	<1 µg/l	<1	µg/l	
Copper	1.5 µg/l	3 µg/l	<1 µg/l	2 +/-	1 µg/l	
Lead	<1 µg/l	<1 µg/l	<1 µg/l	<1	µg/l	
Nickel	3 µg/l	3 µg/l	1 µg/l	2 +/-	1 µg/l	
Strontium	78 µg/l	85 µg/l	49 µg/l	70 +/-	16 µg/l	
Zinc	14.5 µg/l	19.5 µg/l	53 µg/l	29 +/-	17 µg/l	
Specific conductance	116 µS/cm	125 µS/cm	142 µS/cm	127 +/-	11 µS/cm	
pH	6.6	6.4	6.7	—	—	

[Units are milligrams per liter (mg/l), micrograms per liter (µg/l), or microsiemens per centimeter (µS/cm) at 25 degrees Celsius; some wells were sampled more than once and values are means for concentrations detected; mean was calculated by dividing the sum of the concentrations by the number of analyses for each well; single values for mean +/- standard deviation shows the concentration detected in one sample; < indicates less than; —, indicates not determined.]

cipitation of barium, boron, or strontium mineral phases was minimal in the geochemical environments of the leachate plume, alluvial aquifer, and Memphis aquifer (solubility constraints will be discussed in the following section). Barium and especially strontium remain dissolved during transport in these low ionic strength (I) ground waters ($I = \frac{1}{2} \sum (\text{concentration}) (\text{charge})^2$, using all constituent concentrations listed in Table 1 except cadmium, chromium, copper, lead, nickel, and zinc; $I = 0.002$ to 0.009 in the model-generated ground-water mixtures). Boron exists primarily as undissociated boric acid (H_3BO_3) in the pH range of 5.2 to 6.9 measured in samples from these wells.

In summary, barium, boron, chloride, and strontium data from these waters were tested as tracers of the plume away from the landfill. The extent to which each constituent fulfills the criterion of conservative behavior is discussed in the following section.

Tracing the leachate plume into the Memphis aquifer through discontinuities in the confining layer was difficult. In the Memphis aquifer, concentrations of calcium, dissolved solids, potassium, sodium, and strontium were significantly higher in samples collected proximal to the discon-

tinuity in the confining layer, in comparison to samples from background and distal wells (Table 2). Barium, boron, and chloride also were measured at elevated concentrations in some proximal Memphis aquifer samples, but not at statistically significant mean concentrations. Highest inorganic constituent concentrations were measured in samples from well MS-11, where the confining unit is thin (Figure 1). However, volatile organic compounds were detected in samples from all proximal Memphis aquifer wells (Parks and Mirecki, 1992) so data from MS-7, MS-11, and MS-12 were averaged for interpretation.

Concentrations of volatile organic compounds were not input parameters for the geochemical model code PHREEQE (Parkhurst et al., 1980) used in this study. Volatile organic compounds (primarily benzene, chloroethane, dichloromethane, 1,1-dichloroethane, ethylbenzene, tetrachloroethylene, and trifluoromethane) were detected at concentrations of 1 to 12 micrograms per liter (µg/l) in wells MS-7, MS-11, and MS-12 screened in the Memphis aquifer (Parks and Mirecki, 1992). The presence of synthetic volatile organic compounds and elevated concentrations of major and trace inorganic constituents indicated that leachate has

travelled from the landfill in the alluvial aquifer toward the depression in the potentiometric surface, and has entered the Memphis aquifer as a result of downward leakage.

Geochemical Modeling

The geochemical model code PHREEQE (pH-redox equilibrium equations) (Parkhurst et al., 1980) was used to estimate the percentage of contaminated alluvial aquifer water in Memphis aquifer samples. For these model calculations, mean concentrations of leachate-contaminated alluvial aquifer samples (from wells downgradient from the landfill; Table 1) were mixed in varying proportions with mean concentrations of uncontaminated Memphis aquifer samples (background wells; Table 2). The resultant concentrations of barium, boron, chloride, and strontium in these mixtures were used to prepare dilution curves, which related model-generated solute concentrations of inorganic tracers to the percentage of contaminated alluvial aquifer water (Figure 4). Equations describing the dilution curves were used to estimate the percentage of contaminated alluvial aquifer water in Memphis aquifer samples (from wells MS-7, MS-11, and MS-12) collected proximal to the landfill (Table 3).

Equations describing model dilution curves for barium, boron, chloride, and strontium were calculated by applying least-squares regression analysis to mixture data generated by PHREEQE. The slopes of these curves are similar but

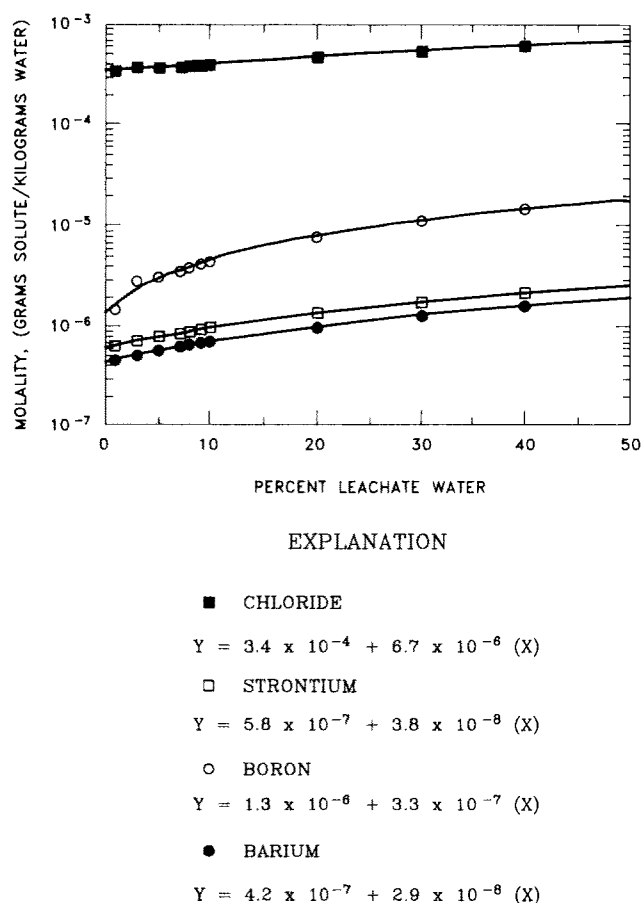


Fig. 4. Dilution curves prepared from mixture data generated by the geochemical model code PHREEQE.

Table 3. Estimated Percentage of Leachate Plume Water in Affected Memphis Aquifer Samples (Wells MS-7, MS-11, and MS-12)

Barium			
equation defining dilution curve: $Y = 4.2 \times 10^{-7} + 2.9 \times 10^{-8} (X)$			
Memphis aquifer sample	Observed concentration $\mu\text{g/l}$	molal	% Leachate plume water
MS-7	81	5.9×10^{-7}	5.9
MS-11	86	6.2×10^{-7}	6.9
MS-12	77	5.6×10^{-7}	4.8
Boron			
equation defining dilution curve: $Y = 1.3 \times 10^{-6} + 3.3 \times 10^{-7} (X)$			
Memphis aquifer sample	Observed concentration $\mu\text{g/l}$	molal	% Leachate plume water
MS-7	25	2.4×10^{-7}	0
MS-11	65	6.0×10^{-7}	0
MS-12	25	2.4×10^{-7}	0
Chloride			
equation defining dilution curve: $Y = 3.4 \times 10^{-4} + 6.7 \times 10^{-6} (X)$			
Memphis aquifer sample	Observed concentration mg/l	molal	% Leachate plume water
MS-7	10.3	2.9×10^{-4}	0
MS-11	61	1.7×10^{-3}	greater than 100
MS-12	8.4	2.4×10^{-4}	0
Strontium			
equation defining dilution curve: $Y = 5.8 \times 10^{-7} + 3.8 \times 10^{-8} (X)$			
Memphis aquifer sample	Observed concentration $\mu\text{g/l}$	molal	% Leachate plume water
MS-7	82	9.5×10^{-7}	9.7
MS-11	130	1.5×10^{-6}	24
MS-12	171	2.0×10^{-6}	37

[The percentage of contaminated alluvial aquifer water was calculated using measured concentrations of barium, boron, chloride, and strontium from affected samples in equations from model-generated dilution curves (Figure 4). In the dilution curve equations, the X variable is % leachate plume water, and the Y variable is observed concentration (molal).]

not identical, indicating that some constituents react (that is, are semiconservative) as they move away from the landfill (Figure 4). Saturation indices (SI: $\log [\text{Ion Activity Product}/K_{\text{sp}} \text{ } T^{\circ}\text{C}]$ where $T^{\circ}\text{C}$ is temperature in degrees Celsius of the ground-water samples) listed in the PHREEQE output showed which constituents were involved in precipitation-dissolution reactions (see Appendix). Positive values for the SI suggested that barite (BaSO_4) should precipitate in mixtures composed of 25 to 100 percent contaminated alluvial aquifer water. Negative SI values were obtained for celestite (SrSO_4) and strontianite (SrCO_3) in all cases, indicating that these waters were undersaturated with respect to celestite and strontianite (see Appendix). Chloride salts did not precipitate in these low ionic strength conditions.

Some boundary conditions were estimated in the PHREEQE model, specifically regarding the redox state (p_e : $-\log\{\text{electron}\}$) of the leachate plume. Dissolved ferrous (Fe^{2+}) and ferric (Fe^{3+}) iron and dissolved hydrogen sulfide (H_2S) concentrations in ground waters were not measured. However, iron oxide or hydroxide (presumably goethite, $\alpha\text{-FeOOH}$, at this pH and Fe concentration range; Stumm and Morgan, 1981) was identified in auger- and test-hole cuttings from the alluvium, downgradient from the landfill (Appendix B, Parks and Mirecki, 1992), as was the odor of hydrogen sulfide during drilling. Iron oxide precipitation and sulfate reduction suggested a p_e range of 0 to -2 , given that pH measurements ranged from 5.2 to 6.9 in both alluvial and Memphis aquifers (Parks and Mirecki, 1992). All model mixtures were run with a $p_e = 0$. Precise evaluation of the redox environment is not critical for evaluation of dissolved boron, chloride, and strontium mobility because these constituents are not overly sensitive to changes in p_e . However, the p_e conditions of leachate can affect the distribution of sulfate and, consequently, the solubility of corresponding sulfate mineral phases such as barite and celestite. The redox conditions of the leachate plume near the landfill were assumed to be reducing based on the odor of hydrogen sulfide, and generally low sulfate concentrations in samples from downgradient alluvial aquifer wells (Table 1).

As the plume became more dilute away from the landfill, redox conditions became more oxidizing, as suggested by higher sulfate concentrations in samples from distal Memphis aquifer wells (Table 2). An oxidizing environment favors precipitation of sulfate minerals, especially barite. However, barium and strontium concentrations diminish by dilution so that water samples from the distal region of the flow path are undersaturated with respect to barite and celestite (see Appendix). Because the geochemical environment is defined by changing redox conditions and mineral solubilities, barite seems to precipitate only in a limited region along the leachate flow path. Barite precipitation will result in an underestimation of the percentage of contaminated alluvial aquifer water in some ground-water samples proximal to the landfill.

It was assumed that the contribution of barium, boron, chloride, and strontium from desorption or dissolution of quartz sand, gravel, silt, and clay was insignificant. Adsorption by clays would reduce cation concentrations in proximal ground-water samples. Because the Memphis Sand is quartz sand, adsorption and desorption reactions were assumed to be negligible.

The effect of the leachate plume on water quality of selected Memphis aquifer samples can be estimated by fitting concentration data from affected samples to the model-generated dilution curves (Table 3; Figure 4). The leachate component calculated in samples from Memphis aquifer wells MS-7, MS-11, and MS-12 ranged from 5 to 7 percent using barium as a tracer, 0 percent using boron, 0 to 100 percent using chloride, and 10 to 37 percent using strontium (Table 3). Of these four constituents, barium and strontium probably serve as the most reliable tracers of the leachate plume for several reasons. First, strontium likely behaves

conservatively, as indicated by negative saturation indices for celestite and strontianite (see Appendix). Second, barium and strontium probably behave similarly in the leachate plume, as indicated by similar slopes of the model-generated dilution curves (Figure 4).

Ideally, chloride and boron should serve as conservative tracers because they are nonreactive in dilute solutions. Chloride anions should not precipitate as mineral phases or adsorb extensively onto clay surfaces. However, due to extensive variations in chloride and boron concentrations (coefficients of variation ranged between 25 and 100 percent in downgradient alluvial aquifer and Memphis aquifer samples), estimates of the leachate component ranged from 0 to 100 percent for these constituents.

Summary and Conclusions

Concentrations of selected inorganic constituents, specifically barium, boron, chloride, and strontium, were shown to identify the leachate plume emanating from Shelby County landfill at Memphis, Tennessee. In the alluvial aquifer, barium, boron, chloride, and strontium concentrations in samples from downgradient wells were elevated at a statistically significant level above those concentrations measured in upgradient and background samples. Elevated concentrations of barium, boron, chloride, and strontium persisted as the leachate plume moved away from the landfill toward a depression in the potentiometric surface of the alluvial aquifer.

Most likely, ground water did not seep continuously through the landfill, or flow at the same velocity in the alluvial aquifer toward the depression in the potentiometric surface. Instead, ground-water movement through the landfill was affected by recharge from precipitation, and in the alluvial aquifer by the stage of the Wolf River. These relations suggest that leachate probably flows away from the landfill in the alluvial aquifer as discrete "pulses" along preferential flow paths rather than as a continuous plume. These physical factors may explain the variability observed in this geochemical data set.

Using the geochemical model code PHREEQE, ground-water mixtures were generated using different proportions of leachate plume water (mean concentrations of downgradient wells in the alluvial aquifer) mixed with uncontaminated Memphis aquifer water (mean concentrations from background samples). Comparison of these model-generated mixtures with measured concentrations from contaminated Memphis aquifer samples allowed estimation of the percentage of leachate water in these Memphis aquifer samples.

Of the four tracers used, barium and strontium seemed to behave conservatively. Saturation indices suggest that strontium did not precipitate as a mineral phase along the flow path. Barium concentrations approached saturation, such that barite could have precipitated in mixtures composed of 25 to 100 percent contaminated alluvial aquifer water. Use of barium as a tracer indicated that the leachate component ranged between 5 and 7 percent; use of strontium indicated that the leachate component ranged between

10 and 37 percent in contaminated Memphis aquifer samples.

Appendix

PHREEQE output of saturation indices (log [Ion Activity Product/ K_{sp} T°C]) for barite, celestite, and strontianite in initial solutions (from Tables 1 and 2) and model-generated mixtures. Positive values indicate precipitation, negative values indicate dissolution. Percent mix represents the percent of contaminated alluvial aquifer water mixed with background Memphis aquifer water.

Mineral	100% contaminated alluvial aquifer	100% Memphis aquifer
Barite	0.399	-0.360
Celestite	-3.015	-3.775
Strontianite	-4.355	-5.140

Mineral	40% mix	30% mix	20% mix	10% mix	9% mix
Barite	0.136	0.063	-0.031	-0.159	-0.175
Celestite	-3.287	-3.361	-3.454	-3.581	-3.596
Strontianite	-4.649	-4.726	-4.821	-4.947	-4.963

Mineral	8% mix	7% mix	6% mix	5% mix	1% mix
Barite	-0.191	-0.208	-0.227	-0.246	-0.335
Celestite	-3.612	-3.629	-3.647	-3.665	-3.750
Strontianite	-4.979	-4.995	-5.031	-5.067	-5.116

References

- Baedecker, M. J. and W. Back. 1979. Hydrogeological processes and chemical reactions at a landfill. *Ground Water*. v. 17, no. 5, pp. 429-437.
- Bolton, K. A. and L. J. Evans. 1991. Elemental composition and speciation of some landfill leachates with particular reference to cadmium. *Water, Air, and Soil Pollution*. v. 60, pp. 43-53.
- Borden, R. C. and T. M. Yanoschak. 1990. Ground and surface water quality impacts of North Carolina sanitary landfills. *Water Resources Bulletin*. v. 26, no. 2, pp. 269-277.
- Bradley, M. W. 1991. Ground-water hydrology and the effects of vertical leakage and leachate migration on ground-water quality near the Shelby County landfill, Memphis, Tennessee. U.S. Geological Survey Water-Resources Investigations Report 90-4075. 42 pp.
- Dewalle, F. B. and E.S.K. Chian. 1981. Detection of trace organics in well water near a solid waste landfill. *Journal of the American Water Works Association*. v. 73, pp. 206-211.
- Domenico, P. A. and F. W. Schwartz. 1990. *Physical and Chemical Hydrogeology*. John Wiley and Sons, New York, NY. p. 78.
- MacFarlane, D. S., J. A. Cherry, R. W. Gillham, and E. A. Sudicky. 1983. Migration of contaminants in a ground-water at a landfill: A case study. 1. Groundwater flow and plume delineation. *Journal of Hydrogeology*. v. 63, pp. 1-29.
- Parkhurst, D. L., D. C. Thorstenson, and L. N. Plummer. 1980. PHREEQE—A computer program for geochemical calculations. U.S. Geological Survey Water-Resources Investigations Report 80-96. 193 pp.
- Parks, W. S. 1990. Hydrogeology and preliminary assessment of the potential for contamination of the Memphis aquifer in the Memphis area, Tennessee. U.S. Geological Survey Water-Resources Investigations Report 90-4092. 39 pp.
- Parks, W. S. and J. E. Mirecki. 1992. Hydrogeology, ground-water quality, and potential for water-supply contamination near the Shelby County landfill in Memphis, Tennessee. U.S. Geological Survey Water-Resources Investigations Report 91-4173. 79 pp.
- Reinhard, M., N. L. Goodman, and J. F. Barker. 1984. Occurrence and distribution of organic chemicals in two landfill leachate plumes. *Environmental Science and Technology*. v. 18, pp. 953-961.
- Russell, G. M. and A. L. Higer. 1988. Assessment of ground-water contamination near Lantana landfill, southeast Florida. *Ground Water*. v. 26, no. 2, pp. 156-164.
- Stumm, W. and J. J. Morgan. 1981. *Aquatic Chemistry* (2nd ed.). John Wiley and Sons, New York, NY. pp. 232-233.
- U.S. Environmental Protection Agency. 1991a. Hazardous waste management system: Amendments to interim status standards for downgradient ground-water monitoring well locations at hazardous waste sites. *Federal Register*. v. 56, no. 246, October 9, 1991, pp. 66365-66369.
- U.S. Environmental Protection Agency. 1991b. Guidelines for the land disposal of solid wastes. Code of Federal Regulations. 40 CFR part 240.204 Water quality. p. 266.
- U.S. Environmental Protection Agency. 1991c. Criteria for classification of solid waste disposal facilities and practices. Code of Federal Regulations. 40 CFR part 257.3-4 Ground water. p. 349.